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DEFENSE NUCLEAR AGENCY REACTION RATE
HANDBOOK. SECOND EDITION.
REVISED NUMBER 3

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General Electric Company

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MEMORANDUM

TO: All Recipients of the DNA Reaction Rate Handbook
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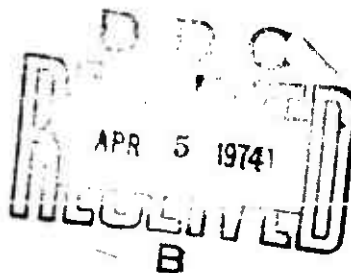
FROM: The Editors

Enclosed herewith you will find a copy of Revision Number 3 to the Handbook. It is comprised of a complete revision of Chapter 24, Summary of Suggested Rate Constants.

You should immediately substitute the enclosed item into your copy of the Handbook, discarding the corresponding pages which they replace.

You should also enter on page iii in front of your Handbook the following information: Revision No. 3; Date of Issue- September 1973; Date of Receipt- whatever day you receive this; and sign your name in the last column.

Revision Number 2, which was expected to be issued during the summer of 1973 has been delayed for various reasons and will be published in the near future. Thank you for your patience and cooperation.



24. SUMMARY OF SUGGESTED RATE CONSTANTS

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(Latest Revision 1 September 1973)

24.1 INTRODUCTION

This chapter presents in Table 24-1 a summary of reactions, with suggested rate coefficients, relevant to the problems of atmospheric chemical recovery following a perturbation. The present generation of computers permits the convenient handling of large numbers of reactions in relation to the solution of such problems. Thus, one may now include in detailed calculations of this type, hundreds of individual reactions, and follow the complete histories of large numbers of individual species as atmospheric constituents. Many computer codes exist, e.g., the Keneshea code (Reference 24-1), which have been designed for the study of atmospheric reactions, and are capable of carrying out the appropriate calculations. Such codes are in use at various institutes and laboratories throughout the country. In order to promote communications among these installations it is convenient to have one standard set of rate coefficients which are recognized universally as valid for all common purposes, e.g., the comparative solution of test problems, or the complementary solution of different aspects of one large problem.

24.2 PRESENTATION OF REACTIONS
AND RATE DATA

The reactions are listed in Table 24-1 by type, in the same order as the reaction types given in Chapter 6 (Table 6-1); however, the type numbers used are not the same in the two tabulations. For each reaction type, i.e., within each section of Table 24-1, reactions are usually listed according to the identity of the more energetic reactant, and in the following order: oxygen and nitrogen or "pure air" species, hydrogen species, carbon species, metallic species. For each such group of species, the suborder of listing is: monatomic, diatomic, triatomic, polyatomic, and complex or clustered.

Wherever the authors of the various chapters of this Handbook have recommended specific values for the reaction rate constants

or coefficients, those values are used in Table 24-1. However, such data are either uncertain or unavailable for certain reactions which are nevertheless considered sufficiently important to be included. Values of these rate constants or coefficients have been estimated, either by an appropriate expert, e.g., the cognizant chapter author, or by a committee of knowledgeable workers. These cases are annotated accordingly (in the "Sources" column of the table) as either a rather good estimate (Est.) or a somewhat shakier "guesstimate" (Gst.) IT SHOULD BE STRESSED THAT, INASMUCH AS A SIGNIFICANT NUMBER OF THE REACTIONS LISTED MAY BE CHARACTERIZED IN ONE OF THESE FASHIONS, ONE SHOULD BE EXTREMELY CAREFUL NOT TO CONSIDER THESE RATES AS FINAL. In several cases the indicated degree of uncertainty is based on the unavailability of any experimental data for the reaction considered. Where this is true, a notation to that effect is included among the applicable notes. There are, perhaps, many more reactions in Table 24-1 to which such a designation should have been applied than has actually been the case.

It may be argued by some Handbook users that many of the reactions listed are not important. This is perhaps true under certain sets of conditions, in which case the reactions may be totally ignored, or alternatively their rates may be set equal to zero for coding purposes. However, under other, equally important circumstances, these same reactions may either contribute directly to or act as precursors of other processes which are influential within the given context. On the other hand, although the numbers of reactions and species included in the table are large, there certainly are some important omissions as well, since it can be anticipated that particular reactions, not yet thought to be of any importance to the deionization problem, or perhaps not yet even conceived of, may be found in the future to play some weighty role in the overall atmospheric chemical scheme.

In Table 24-1, the rate coefficients are presented in cgs units, i.e., in sec^{-1} , $\text{cm}^3 \text{sec}^{-1}$, and $\text{cm}^6 \text{sec}^{-1}$ for one-, two-, and three-body processes, respectively. Species densities are in cm^{-3} and temperature in K. The letter "M" is used to represent a collision partner; unless specifically noted otherwise, it represents any possible species present and acting as catalyst. The numerical notation $[-x]$ signifies multiplication by 10^{-x} . Most rate functions "k" are represented by sets of numbers "a", "b", and "c", which refer in turn to the formulation:

$$k = a(T/300)^b \exp(-c/T) ,$$

where 300 in the first parenthesized term is the usual reference temperature (in K), unless another T_{ref} is designated in the table. A few rate functions follow a more complex variation with temperature than that given above, or are dependent on other parameters as well, e.g., local species densities. These complex functions are presented in brackets, transcending the usual format of the table. Elsewhere, only the coefficient "a" is itself density-dependent rather than constant. Here, too, brackets are used.

The temperature dependence mentioned above refers in most instances to the ordinary gas-kinetic or translational temperature T or T_{gas} . However, certain reaction rates turn out to depend preferentially upon specialized temperatures, which are here designated accordingly, e.g., the kinetic temperature of interacting electrons (T_e) or ions (T_i), and the vibrational temperature of interacting molecules (T_v) or ions (T_{iv}).

A high degree of uncertainty for some of the data was implied in preceding paragraphs of this discussion. This uncertainty is particularly appropriate to the values of the exponent "b" in the above mathematical expression. For example, little or no experimental knowledge of the temperature dependence (to which "b" relates directly) is available for many exothermic reactions, which have been observed primarily at laboratory temperatures. Moreover, most of the reactions included in Table 24-1 are indeed exothermic, despite two recent trends, viz.: (a) an increasing emphasis within the atmospheric effects community on the study of high-temperature (including endothermic) processes; and hence (b) the inclusion of more endothermic reactions in the present edition of the Handbook than in its predecessor.

Wherever, in Table 24-1, $c \neq 0$, it follows that the rate constant at 300 K is unequal to the listed value of the "a" parameter; in all such cases the rate constant at 300 K, k_{300} , has been calculated from the three parameters and is listed in the "Notes" column. Such values are not to be construed as implying actual measurement at 300 K, unless specifically so stated in the table.

Finally, it should be noted that for a few reactions, e.g., in Section XX, some unusually high values of the "a" parameters are tabulated. These appear to fit the available data (Reference 24-2), but

more work is obviously needed. In some cases the reaction products are uncertain, and the noncommittal notation, "Products", is provided in the reaction equation itself, as an alternative to any guess or "guess-timate" as to the true identities of specific products.

Table 24-1. Reactions and suggested rate constants.
 $k = a(1/300)^b e^{-c/T}$

No.	Reaction	a	b	c	Notes	Sources
I. Radiative Recombination:						
1.	$O^+ + e \rightarrow O + h\nu$	$(3.5 \pm 1.0) \times 10^{-12}$	(-0.7 ± 0.1)	0	Very small compared to dissociative recombination	Chp. 16
2.	$N^+ + e \rightarrow N + h\nu$	$(3.5 \pm 1.0) \times 10^{-12}$	(-0.7 ± 0.1)	0		
3.	$H^+ + e \rightarrow H + h\nu$	$(3.5 \pm 1.0) \times 10^{-12}$	(-0.7 ± 0.1)	0		
4.	$O_2^+ + e \rightarrow O_2 + h\nu$	$(4) \times 10^{-12} \pm 1$	(-0.7 ± 0.5)	0		
5.	$N_2^+ + e \rightarrow N_2 + h\nu$	$(4) \times 10^{-12} \pm 1$	(-0.7 ± 0.5)	0		
6.	$NO^+ + e \rightarrow NO + h\nu$	$(4) \times 10^{-12} \pm 1$	(-0.7 ± 0.5)	0		
II. Photoionization:						
1.a.	$O + h\nu \rightarrow O^+(^4S) + e$				Wavelength and flux dependent	Chps. 12, 13
b.	$- O^+(^2D) + e$					
c.	$- O^+(^2P) + e$					
2.a.	$N_2 + h\nu \rightarrow N_2^+ + e$					
b.	$- N^+ + e + N$					
3.a.	$O_2 + h\nu \rightarrow O_2^+ + e$					
b.	$- O^+ + e + O$					
4.	$NO + h\nu \rightarrow NO^+ + e$					
III. Three-Body Recombination:						
1.a.	$X^+ + e + M \rightarrow \text{Products}$	$(2) \times 10^{-27.0 \pm 0.2}$ $(6) \times 10^{-27.0 \pm 0.3}$ $(3) \times 10^{-26.0 \pm 0.3}$	(-2.5) (-2.5) (-2.5)	0 0 0	X^+ = atomic ion M = atom M = molecule M = polar molecule	Chp. 16 + Est.

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
III. Three-Body Recombination (Cont'd.):						
1.b.	$XY^+ + e + M \rightarrow \text{Products}$	$(6) [-27.0 \pm 0.3]$ $(3) [-26.0 \pm 0.3]$	(-2.5) (-2.5)	0 0	$XY^+ = \text{molecular ion}$ $M = \text{atom or molecule}$ $M = \text{polar molecule}$	Chp. 16 + Est.
c.	$X^+(\text{cluster}) + e + M \rightarrow \text{Products}$	$(5) [-26.0 \pm 0.3]$	(-2.5)	0	$X^+(\text{cluster}) = \text{any clustered ion}$ $M = \text{any third body}$	Gst.
2.a.	$X^+ + e + e \rightarrow \text{Products}$	$(7 \pm 3) [-20]$	(-4.5)	0	$X^+ = \text{any atomic or molecular ion}$	Chp. 16
b.	$X^+(\text{cluster}) + e + e \rightarrow \text{Products}$	$(3) [-19.0 \pm 0.3]$	(-4.5)	0	$X^+(\text{cluster}) = \text{any clustered ion}$	Gst.
IV. Dissociative Recombination:						
1.a.	$O_2^+ + e \rightarrow O + O$	$(2.1 \pm 0.2) [-7]$ (-0.63 ± 0.07)		0	$T = T_e$ For $T_{iv} > \sim 1000$ K, multiply above formula by a factor $(1 - \exp(-2677/T_{iv}))$.	Chp. 16 + Est.
b.	$-1.0 O(^3P) + 0.9 O(^1D) + 0.1 O(^1S)$	$(2.1 \pm 0.2) [-7]$ (-0.63 ± 0.07)		0	$T = T_e$ Branching measured at 300 K; branching ratio probably changes with increasing T.	
2.a.	$N_2^+ + e \rightarrow N + N$	$(1.8^{+0.4}_{-0.2}) [-7]$ (-0.39)		0	$T = T_e$ For $T_{iv} > \sim 1200$ K, multiply above formula by a factor $(1 - \exp(-3152/T_{iv}))$.	
b.	$-1.68 N(^2D) + 0.92 N(^4S)$	Theoretical branching ratio.				Est. (Ref. 24-3)

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources	
IV. Dissociative Recombination (Cont'd.):							
3.a.	$\text{NO}^+ + e \rightarrow \text{N} + \text{O}$	$(4.0 \pm 0.3) \times 10^{-7}$	(-1.0 ± 0.2)	0	$T = 200\text{--}300 \text{ K}$	Chp. 16	
b.	$\text{N} + \text{O}$	$(4.0 \pm 0.3) \times 10^{-7}$	(-0.8 ± 0.2)	0	$T = T_e$	Chp. 16 + Est. (Ref. 24-4)	
c.	$-\text{N}(^3\text{D}) + \text{O}(^3\text{P})$	For $T_{1/2} > \sim 1300 \text{ K}$, multiply above formula by a factor $[1 - \exp(-3230/T_{1/2})]$.					Est. (Ref. 24-3)
Theoretical prediction							
4.	$\text{N}_3^+ + e \rightarrow \text{N} + \text{N}_2$	$(7 \pm 4) \times 10^{-7}$	(-1.0 ± 0.5)	0		Est.	
5.	$\text{N}_4^+ + e \rightarrow \text{N}_2 + \text{N}_2$	$(2 \pm 1) \times 10^{-6}$	(-1.0 ± 0.3)	0		Chp. 16	
6.	$\text{NO}_2^+ + e \rightarrow \text{Products}$	$(3 \pm 2) \times 10^{-7}$	(-0.5 ± 0.2)	0	$T = T_e$	Est.	
7.	$\text{NO}^+ \cdot \text{NO} + e \rightarrow \text{NO} + \text{NO}$	$(1.7 \pm 0.5) \times 10^{-6}$	(-1.0 ± 0.5)	0		Chp. 16 + Est.	
8.	$\text{NO}^+ \cdot \text{H}_2\text{O} + e \rightarrow \text{N} + \text{O} + \text{H}_2\text{O}$	$(1) \times 10^{-6}$	$(-0.2^{+0.2}_{-0.8})$	0		Est.	
9.	$\text{NO}^+(\text{H}_2\text{O})_2 + e \rightarrow \text{N} + \text{O} + 2\text{H}_2\text{O}$	$(2) \times 10^{-6}$	$(-0.2^{+0.2}_{-0.8})$	0			
10.	$\text{NO}^+(\text{H}_2\text{O})_3 + e \rightarrow \text{N} + \text{O} + 3\text{H}_2\text{O}$	$(3) \times 10^{-6}$	$(-0.2^{+0.2}_{-0.8})$	0			
11.	$\text{O}_2^+ \cdot \text{O}_2 + e \rightarrow \text{O} + \text{O} + \text{O}_2$	$(2.0 \pm 0.5) \times 10^{-6}$	(-1.0 ± 0.5)	0	Products Uncertain	Chp. 16	
12.	$\text{O}_2^+ \cdot \text{H}_2\text{O} + e \rightarrow \text{O} + \text{O} + \text{H}_2\text{O}$	$(1.5) \times 10^{-6}$	$(-0.2^{+0.2}_{-0.8})$	0		Est.	
13.	$\text{H}_3\text{O}^+ + e \rightarrow \text{H}_2\text{O} + \text{H}$ $\quad \quad \quad \rightarrow \text{H}_2 + \text{OH}$	$(1.3 \pm 0.3) \times 10^{-6}$	$(-0.2^{+0.1}_{-0.4})$	0		Chp. 16	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
IV. <u>Dissociative Recombination (Cont'd.):</u>						
14.	$\text{H}_3\text{O}^+ \cdot \text{H}_2\text{O} + e \rightarrow 2\text{H}_2\text{O} + \text{H}$ - $\text{H}_2 + \text{OH} + \text{H}_2\text{O}$	$(2.8 \pm 0.4) -6 $	$(-0.2^{+0.1}_{-0.4})$	0	Products uncertain	Chp. 16
15.	$\text{H}_3\text{O}^+ (\text{H}_2\text{O})_2 + e \rightarrow 3\text{H}_2\text{O} + \text{H}$ - $\text{H}_2 + \text{OH} + 2\text{H}_2\text{O}$	$(5.1 \pm 0.7) -6 $	$(-0.2^{+0.1}_{-0.4})$	0		
16.	$\text{H}_3\text{O}^+ (\text{H}_2\text{O})_3 + e \rightarrow 4\text{H}_2\text{O} + \text{H}$ - $\text{H}_2 + \text{OH} + 3\text{H}_2\text{O}$	$(6.1 \pm 1.2) -6 $	$(-0.2^{+0.1}_{-0.4})$	0		
17.	$\text{H}_3\text{O}^+ (\text{H}_2\text{O})_4 + e \rightarrow 5\text{H}_2\text{O} + \text{H}$ - $\text{H}_2 + \text{OH} + 4\text{H}_2\text{O}$	$(7.4 \pm 1.5) -6 $	$(-0.2^{+0.1}_{-0.4})$	0		
18. ^a	$\text{H}_3\text{O}^+ (\text{H}_2\text{O})_5 + e \rightarrow 6\text{H}_2\text{O} + \text{H}$ - $\text{H}_2 + \text{OH} + 5\text{H}_2\text{O}$	$(9.3 \pm 2.0) -6 $	$(-0.2^{+0.1}_{-0.4})$	0		
19.	$\text{H}_3\text{O}^+ \cdot \text{OH} + e \rightarrow \text{H}_2\text{O} + \text{H} + \text{OH}$ - $\text{H}_2 + \text{CH} + \text{OH}$	$(3) -6 $	(-1.0 ± 0.5)	0	Est.	
V. <u>Mutual Neutralization:</u>						
1.	$\text{O}^+ + \text{O}^- \rightarrow \text{O} + \text{O}$	$(2.7 \pm 1.3) -7 $	(-0.5)	0		Chp. 16
2.	$\text{O}_2^+ + \text{O}^- \rightarrow \text{Products (probably } \text{O}_2 + \text{O)}$	$(9.6 \pm 3.0) -8 $	(-0.5)	0		
Note: ^a For the analogous reactions for higher hydrates, i.e., $\text{H}_3\text{O}^+ (\text{H}_2\text{O})_n$, where $n \geq 6$, use the rate coefficients for Reaction IV. 18.						

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
V. Mutual Neutralization (Cont'd.):						
3.	$O_2^+ + O_2^- \rightarrow \text{Products}$ (probably $O_2 + O_2$)	$(4.2 \pm 1.3)[-7]$	(-0.5)	0		Chp. 16
4.	$O_2^+ + NO_2^- \rightarrow \text{Products}$ (probably $O_2 + NO_2$)	$(4.1 \pm 1.3)[-7]$	(-0.5)	0		
5.	$O_2^+ + NO_3^- \rightarrow \text{Products}$ (probably $O_2 + NO_3$)	$(1.3 \pm 0.5)[-7]$	(-0.5)	0		
6.	$N_2^+ + O_2^- \rightarrow \text{Products}$ (probably $N_2 + O_2$)	$(1.6 \pm 0.5)[-7]$	(-0.5)	0		
7.	$NO^+ + O^- \rightarrow \text{Products}$ (probably $NO + O$)	$(4.9 \pm 1.5)[-7]$	(-0.5)	0		
8.	$NO^+ + NO_2^- \rightarrow \text{Products}$ (probably $NO + NO_2$)	$(3.5 \pm 2.4)[-7]$	(-0.5)	0		
9.	$NO^+ + NO_3^- \rightarrow \text{Products}$ (probably $NO + NO_3$)	$\begin{pmatrix} 4^{+5} \\ -3 \end{pmatrix} [-7]$	(-0.5)	0		
10.	$N^+ + O^- \rightarrow N + O$	$(2.6 \pm 0.8)[-7]$	(-0.5)	0		
11.	$X^+ + Y^- \rightarrow \text{Products (probably } X + Y)$	$\begin{pmatrix} 1.0^{+4.0} \\ -0.9 \end{pmatrix} [-7]$	(-0.5)	0	X^+ and Y^- are either atomic or molecular.	Est.
12.	$X^+(\text{cluster}) + Y^- \rightarrow \text{Products}$	$(5)[-7.0 \pm 0.3]$	(-0.5)	0	$\left. \begin{matrix} X^+(\text{cluster}) \text{ and} \\ Y^-(\text{cluster}) \text{ are any} \\ \text{clustered ions.} \end{matrix} \right\}$ Gst.	Gst.
13.	$X^+ + Y^-(\text{cluster}) \rightarrow \text{Products}$	$(5)[-7.0 \pm 0.3]$	(-0.5)	0		
14.	$X^+(\text{cluster}) + Y^-(\text{cluster}) \rightarrow \text{Products}$	$(5)[-7.0 \pm 0.3]$	(-0.5)	0		

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
<u>VI. Three-Body Ion-Ion Recombination:</u>						
1.	$X^+ + Y^- + M \rightarrow \text{Products}$	(3±1)[-25]	(-2.5)	0	X^+ , Y^- , and M are either atomic or molecular "air" species. X^+ (cluster) and Y^- (cluster) are any clustered ions.	Chp. 16 Gst.
2.	$X^+(\text{cluster}) + Y^- + M \rightarrow \text{Products}$	(3±1)[-25]	(-2.5)	0		
3.	$X^+ + Y^-(\text{cluster}) + M \rightarrow \text{Products}$	(3±1)[-25]	(-2.5)	0		
4.	$X^+(\text{cluster}) + Y^-(\text{cluster}) + M \rightarrow \text{Products}$	(3±1)[-25]	(-2.5)	0		
<u>VII. Radiative Attachment:</u>						
1.	$O + e \rightarrow O^- + h\nu$	(1.3±0.1)[-15]	0	0	Slow compared with Reactions XI.2(a, b). See Reaction IX.7. Detailed balance calculation	Chp. 17 Est. Ref. 24-5
2.	$O_2 + e \rightarrow O_2^- + h\nu$	(2)[-19±1]	0	0		
3.	$O_3 + e \rightarrow O_3^- + h\nu$	(1)[-17±3]	0	0		
4.	$NO_2 + e \rightarrow NO_2^- + h\nu$	(1)[-17±2]	0	0		
5.	$OH + e \rightarrow OH^- + h\nu$	(2.5±1.5)[-15]	(-0.25)	0		
<u>VIII. Photodetachment:</u>						
1.	$O^- + h\nu \rightarrow O + e$	(1.4±0.1)[0]	0	0	These values are for normal-incidence unattenuated solar flux at top of earth's atmosphere Very with altitudes and solar zenith angles.	Chp. 17
2.	$O_2^- + h\nu \rightarrow O_2 + e$	(0.33±0.10)[0]	0	0		
3.	$O_3^- + h\nu \rightarrow O_3 + e$	(2±1)[-1]	0	0		

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
VIII. Photodetachment (Cont'd.):						
4.	$O_2^+ + h\nu \rightarrow O_2 + O_2^+ + e$	(2)[0.0±0.3]	0	0	See Reaction XXII. 1.	Ref. 24-6
5.	$NO_2^+ + h\nu \rightarrow NO_2 + e$	(8)[-2±2]	0	0		Ref. 24-7
6.	$NO_3^+ + h\nu \rightarrow NO_3 + e$	(5)[-3±2]	0	0		
7.	$OH^+ + h\nu \rightarrow OH + e$	(1)[C±1]	0	0		
8.	$CO_4^+ + h\nu \rightarrow CO_2 + C_2^+ + e$	(3)[-1±2]	0	0		Chp. 17
IX. Three-Body Attachment:						
1.	$O_2 + e + O \rightarrow O_2^+ + O$	(1)[-31±2]	0	0	No experimental data.	Est.
2.	$O_2 + e + O_2 \rightarrow O_2^+ + O_2$	(1.4±0.2)[-29]	(-1)	600	T = 195-600 K $k_{300} = (1.9±0.3)[-30]$	Chp. 17
3.	$O_2 + e + N_2 \rightarrow O_2^+ + N_2$	(1.0±0.5)[-31]	0	0		
4.	$O_2 + e + H_2O \rightarrow O_2^+ + H_2O$	(1.4±0.2)[-29]	0	0	T = 300-400 K	
5.	$O_2 + e + CO_2 \rightarrow O_2^+ + CO_2$	(3.3±0.7)[-30]	0	0	T = 300-525 K	
6.	$NO + e + M \rightarrow \text{Products}$	(8)[-31]	0	0	M = NO	
7.	$NO_2 + e (+M) \rightarrow NO_2^+ (+M)$	(4)[-11]	0	0	Observed to be a saturated 3-body process. k is the effective 2-body value. See Reaction VII. 4.	

Table 24-1. (Cont'd.)

No.	Reaction	u	b	c	Notes	Sources
<u>X. Collisional Detachment:</u>						
1.	$O^- + O_2 \rightarrow O + e + O_2$	(2.3±1.0)[-9]	0	26,000±3000	$T_i < 20,000$ K $k_{300} = (1.0)[-46]$	Chp. 17
2.	$O^- + N_2 \rightarrow O + e + N_2$	(2.3)[-9, 0±0.5]	0	26,000±3000	$T_i < 20,000$ K $k_{300} = (1.0)[-46]$	
3.	$O_2^- + O \rightarrow O_2 + e + O$	(3.6)[-11]	0	5000	Detailed balance calculation. $k_{300} = (2.1)[-18]$	Ref. 24-8
4.	$O_2^- + N_2 \rightarrow O_2 + e + N_2$	(1.9±0.4)[-12]	(1.5)	4990	$T = 375-600$ K $k_{300} = (1.1±0.2)[-19]$	
5.	$O_2^- + O_2 \rightarrow O_2 + e + O_2$	(2.7±0.3)[-10]	(0.5)	5590	$T = 375-600$ K $k_{300} = (2.2±0.2)[-18]$	Chp. 17
6.	$O_2^- + O_2(e^1\Delta_g) \rightarrow O_2 + e + O_2$	$\begin{pmatrix} 2 \\ -1 \end{pmatrix}[-10]$	0	0		
7.	$O_2^- + H_2O \rightarrow O_2 + e + H_2O$	(5.0)[-9]	0	5000	Detailed balance calculation. $k_{300} = (2.9)[-27]$	Ref. 24-8
8.	$O_2^- + CO_2 \rightarrow O_2 + e + CO_2$	(1.2)[-9]	0	5000	Detailed balance calculation. $k_{300} = (7.0)[-28]$	
<u>XI. Dissociative Attachment:</u>						
1.	$O_2 + e \rightarrow O^- + O$	-	-	-	$k < (1)[-16]$ for $T < 2000$ K Endothermic $c > (4)[4]$ at > 300 K. Strong dependence on T_e at high T_e .	Chps. 17, 20

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XI. Dissociative Attachment (Cont'd.):						
2.a.	$O_3 + e \rightarrow O^- + O_2$	(9±2) -12	(1.5)	0	T = 200-300 K See Reaction VII.3	Chp. 17
b.	$-O_2^- + O$	(1.7) -11.0±0.3	(1.5)	13,200	T = T _e . No dependence on T for T < 360 K k ₃₀₀ = (1.3) -30	Est. based on Ref. 24-9.
XII. Associative Detachment:						
1.	$O^- + O \rightarrow O_2 + e$	$\begin{pmatrix} 2^{+2} \\ -1 \end{pmatrix}$ -10	0	0	k < (5) -15 at T = 300 K and T _i = 300-10,000 K Endothermic c ~ 5000	Chp. 17
2.	$O^- + O_2 \rightarrow O_3 + e$	-	-	-		
3.	$O^- + O_2(b^1\Delta_g) \rightarrow O_3 + e$	$\begin{pmatrix} 3.0^{+3.0} \\ -1.5 \end{pmatrix}$ -10	0	0	Cf. Reaction XV.1.	Chps. 17, 20
4.	$O^- + O_3 \rightarrow O_2 + O_2 + e$	-	-	-	Rate is slow, compared with Reaction XV.2.	Est.
5.	$O^- + N \rightarrow NO + e$	$\begin{pmatrix} 2^{+2} \\ -1 \end{pmatrix}$ -10	0	0	k < (1) -12 at T _i = 300 K	Chp. 17
6.	$O^- + N_2 \rightarrow N_2O^- + e$	-	-	-		
7.	$O^- + NO \rightarrow NO_2 + e$	(2.2±0.5) -10	(-0.56)	0	T _i = 300-2000 K	Ref. 24-10
8.	$O^- + H_2 \rightarrow H_2O + e$	(6.5±1.0) -10	(-0.19)	0	T = T _i < 3000 K	
9.	$O^- + CO \rightarrow CO_2^- + e$	(6±1) -10	(-0.32)	0	T = T _i < 3000 K	
10.	$O_2^- + O \rightarrow O_3 + e$	$\begin{pmatrix} 3.0^{+3.0} \\ -1.5 \end{pmatrix}$ -10	0	0		Chp. 17

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XII. Associative Detachment (Cont'd.):						
11.	$O_2^- + N - NO_2 + e$	$(5.0 \pm 2.5)[-10]$	0	0	No experimental data.	Chp. 17
12.	$O_3^- + O - O_2 + O_2 + e$	$(1) \begin{bmatrix} -11 \\ -2 \end{bmatrix}$	0	0		Est.
13.	$OH^- + O - HO_2 + e$	$\begin{pmatrix} 2 \\ -1 \end{pmatrix} [-10]$	0	0		Ref. 24-11
14.	$CO_3^- + O - CO_2 + O_2 + e$	-	-	-		Chp. 17
XIII. Positive-Ion Charge Transfer:						
1.	$O^+ + H - O + H^+$	$(6.8 \pm 3.0)[-10]$	0	0	T < 1800 K T > 1800 K	Chp. 18A
2.	$O^+ + O_2 - O + O_2^+$	$(2.0 \pm 0.2)[-11]$ (-0.40 ± 0.14) (1.20 ± 0.13)		0		Chp. 18A + Ref. 24-12
3.	$O^+ (^2D) + O_2 - O + O_2^+ (e, A)$	$(1.3 \pm 0.2)[-12]$ $(3) \begin{bmatrix} -10.0^{+0.5} \\ -1.0 \end{bmatrix}$	0	0		Chp. 20
4.	$O^+ + NO - O + NO^+$	-	-	-	Chp. 18A gives $\lambda: (1.3)[-12]$. See Reaction XIV.2. Data at 393 K Cf. Reaction XIV.3.	Chp. 18A
5.	$O^+ + NO_2 - O + NO_2^+$	$(1.6 \pm 0.3)[-9]$	0	0		
6.	$O^+ + N_2O - O + N_2O^+$	$(2.2 \pm 1.0)[-10]$	0	0		
7.	$O^+ + H_2O - O + H_2O^+$	$(2.3 \pm 0.3)[-9]$	0	0		
8.	$O^+ (^2D) + N_2 - O + N_2^+$	$(3)[-10 \pm 1]$	0	0		Chp. 20
9.	$N^+ + O - N + O^+$	$(1)[-12]$	0	0		

Table 24-11. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIII.	Positive-Ion Charge Transfer (Cont'd.):					
10. ^b	$N^+ + O_2 \rightarrow N + O_2^+$	$(2.8 \pm 1.0)[-10]$	$\begin{pmatrix} 0.00^{+0.80} \\ -0.17 \end{pmatrix}$	0	T < 4600 K	Chp. 18A
		$(6 \pm 1)[-11]$	(0.57 ± 0.05)	0	T > 4600 K	
11.	$N^+ + NO \rightarrow N + NO^+$	$(8.0 \pm 2.4)[-10]$	0	0		
12.	$N^+ + H_2O \rightarrow N + H_2O^+$	$(2.6 \pm 0.4)[-9]$	0	0		Ref. 24-13
13.	$N^+ + CO \rightarrow N + CO^+$	$(9 \pm 3)[-10]$	0	0		
14.	$N^+ + CO_2 \rightarrow N + CO_2^+$	$(1.3 \pm 0.4)[-9]$	0	0		
15.	$O_2^+ + NO \rightarrow O_2 + NO^+$	$(6.3 \pm 2.4)[-10]$	0	0		Chp. 18A
16.	$O_2^+ + NO_2 \rightarrow O_2 + NO_2^+$	$(6.6 \pm 2.0)[-10]$	0	0	Cf. Reaction XIV. 10.	
17.	$O_2^+ + Na \rightarrow O_2 + Na^+$	$(6.7)[-10 \pm 1]$	0	0	Cf. Reaction XIV. 2.	
18.	$O_2^+(^4\Pi_u) + N_2 \rightarrow O_2 + N_2^+$	$(5 \pm 4)[-10]$	0	0		

Note:

^b The sum of Reactions XIII. 10 and XIV. 6 represent c overall reaction, as measured experimentally, for which the division into the channels indicated is somewhat uncertain, and for which the energy dependence of the separate branches has not been measured. The rate constant for the overall process (both Reactions) is:

$$k = (5.5 \pm 0.5) \times 10^{-10} \left(\frac{T}{300} \right)^{\begin{pmatrix} 0.00^{+0.80} \\ -0.17 \end{pmatrix}} \text{ at } T < 4600 \text{ K;}$$

$$k = (1.2 \pm 0.2) \times 10^{-10} \left(\frac{T}{300} \right)^{(0.57 \pm 0.05)} \text{ at } T \sim 4600 \text{ K.}$$

These values have been arbitrarily halved between the two channels, as seemingly the most reasonable resolution of the problem at this time. The product N_2 in Reaction XIII. 10 may include some proportion of the (2D) state, but no experimental evidence is available to support any estimates in this regard. This entire footnote was obtained from Ref. 24-12.

Table 24-1. (Cont'd.)

No.	Reaction	σ	b	c	Notes	Sources
XIII. Positive-Ion Charge Transfer (Cont'd.):						
19.	$N_2^+ + O - N_2 - O^+$	(6.6)[-11±1]	-	1945	Gst; no experimental data. ^c Cf. Reaction XIV. 13. $k_{300} = (1)[-13±1]$.	Ref. 24-12
20.	$N_2^+ + N - N_2 - N^+$	-	-	-	$k < (1)[-11]$	Chp. 18A
21. ^d	$N_2^+ + O_2 - N_2 + O_2^+$	(5.0±1.0)[-10]	(-0.8±0.2)	0	T < 3560 K	
22.	$N_2^+ + NO - N_2 + NO^+$	(2.5±0.5)[-13]	(1.4±0.3)	0	T > 3560 K	
23.	$N_2^+ + H_2O - N_2 + H_2O^+$	(3.3±1.5)[-10]	0	0	$N_2(A)$ or $NO^+(a)$ may be formed. This reaction combined with Reaction XIV. 16 add to $k = (2.2)[-9]$	
24.	$N_2^+ + CO_2 - N_2 + CO_2^+$	(9±3)[-12]	0	0	-	Ref. 24-13
25.	$N_2^+ + Ne - N_2 + Ne^+$	(5.8±3.0)[-10]	0	0	-	Chp. 18A
26.	$NO^+ + Na - NO + Na^+$	(7.0±3.0)[-11]	0	0	-	
27.	$NO_2^+ + NO - NO_2 + NO^+$	(2.9±1.0)[-10]	0	0	-	
28.	$H^+ + O - H + O^+$	(3.8±2.0)[-10]	0	0	-	

Notes:

^c However, Rutherford has measured $k = 5 \times 10^{-11}$ at 1 eV, in good agreement with the kinetic parameters here indicated (Ref. 24-12).^d Cf. Reaction XIV. 14.

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIII. Positive-Ion Charge Transfer (Cont'd.):						
29.	$H^+ + NO \rightarrow H + NO^+$	$(1.9 \pm 0.5)[-9]$	0	0	Cf. Reaction XIV.36	Chp. 18A
30.	$OH^+ + O_2 \rightarrow OH + O_2^+$	$(2.0 \pm 0.5)[-10]$	0	0		
31.	$H_2O^+ + O_2 \rightarrow H_2O + O_2^+$	$(2.0 \pm 0.5)[-10]$	0	0		
32.	$CO^+ + O \rightarrow CO + O^+$	$(1.4 \pm 0.8)[-10]$	0	0		
33.	$CO^+ + NO \rightarrow CO + NO^+$	$(3.3 \pm 1.0)[-10]$	0	0		
34.	$CO_2^+ + O \rightarrow CO_2 + O^+$	$(1.0 \pm 0.6)[-10]$	0	0		
35.	$CO_2^+ + O_2 \rightarrow CO_2 + O_2^+$	$(5 \pm 2)[-11]$	0	0		
36.	$CO_2^+ + NO \rightarrow CO_2 + NO^+$	$(1.2 \pm 0.4)[-10]$	0	0		
XIV. Positive Ion-Atom Interchange:						
1.*	$O^+ + N_2 \rightarrow NO^+ + N$	$(1.2 \pm 0.1)[-12]$	(-1.0 ± 0.4)	0	$T < 750$ K	Chp. 18A -
2.	$O^+ + NO \rightarrow O_2^+ + N$	$(8.0 \pm 2.0)[-14]$	(2.0 ± 0.2)	0	$T > 750$ K	
3.	$O^+ + N_2O \rightarrow NO^+ + NO$	-	-	-	$k < (1)[-12]$. See Reaction XIII.1.	Est.
		$(2.3 \pm 1.0)[-10]$	0	0	See Reaction XIII.6.	Chp. 18A
Note:						
* According to Ref. 24-12, it is not necessary in Reaction XIV.1 to distinguish between $T_i(O^+)$ and $T_v(N_2)$, admittedly a surprising new result. Therefore, the rate parameters given are valid for $T = T_i$ or $T = T_v$.						

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive Ion-Atom Interchange (Cont'd.):					
4.	$O^+ + H_2 \rightarrow OH^+ + H$	$(2.0 \pm 0.5)[-9]$	0	0		Chp. 18A
5.	$O^+ + CO_2 \rightarrow O_2^+ + CO$	$(1.1 \pm 0.3)[-9]$	0	0		
6. ^f	$N^+ + O_2 \rightarrow NO^+ + O$	$(2.8 \pm 1.0)[-10]$ $(6 \pm 1)[-11]$	$(0.00^{+0.80}_{-0.17})$ (0.57 ± 0.05)	0	$T < 4600$ K $T > 4600$ K	
7.	$N^+ + H_2 \rightarrow NH^+ + H$	$(5.6 \pm 2.0)[-10]$	0	0		Est.
8.a.	$O_2^+ + N \rightarrow NO^+ + O$	$(1.8 \pm 0.6)[-10]$	0	0		
b.	$-O^+ + NO$	-	-	-	Endothermic by 0.153 eV.	
9.	$O_2^+ + N_2 \rightarrow NO^+ + NO$	$(1)[-16^{+1}_{-3}]$	0	0	Chp. 18A gives $k < (1)[-15]$.	Chp. 18A
10.	$O_2^+ + NO_2 \rightarrow NO^+ + O_3$	0	0	0	$k < (1)[-11]$. Cf. Re- action XIII. 16.	
11.	$O_2^+ + H_2$ - Products	-	-	-	$k < (1)[-11]$	
12.	$O_2^+ + Na \rightarrow NaO^+ + O$	$(7.7 \pm 3.0)[-11]$	0	0	Cf. Reaction XIII. 17.	Est.
13.a.	$N_2^+ + O \rightarrow NO^+ + N$	$(1.4 \pm 0.8)[-10]$	0	0	Cf. Reaction XIII. 19.	
b.	$-NO^+ + 0.5N^+(s) + 0.5N_2^+(D)$				Overall Reaction.	

Note:

^f Cf. Reaction XIII. 10, and its accompanying footnote.

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive Ion-Atom Interchange (Cont'd.):					
14.	$N_2^+ + O_2 \rightarrow NO^+ + NO$	(1)[-7±2]	0	0	Cf. Reaction XIII.21.	Est.
15.	$N_2^+ + H_2 \rightarrow N_2H^+ + H$	(1.7±0.3)[-9]	0	0		
16.	$N_2^+ + H_2O \rightarrow N_2H^+ + OH$	-	-	-	See Reaction XIII.23.	
17.	$NO^+ + O_3 \rightarrow NO_2^+ + O_2$	-	-	-	$k < (1)[-14]$	
18.	$N_3^+ + O_2 \rightarrow \text{Products}$	(1.0±0.3)[-10]	0	0	Date at 200 K. Possible products include: (a) $NO^+ + O + N_2$ (b) $O_2^+ + N + N_2$ and (c) $NO_2^+ + N_2$, in roughly comparable magnitudes.	Chp. 18A
19.	$N_4^+ + O_2 \rightarrow N_2 + N_2 + O_2^+$	(4±1)[-10]	0	0	Date at 200 K.	Est.
20.	$O_2^+ \cdot N_2 + O_2 \rightarrow O_4^+ + N_2$	(1.0±0.5)[-9]	0	0		
21.	$O_2^+ \cdot N_2 + H_2O \rightarrow O_2^+ \cdot H_2O + N_2$	(4±2)[-9]	0	0		
22.	$O_2^+ \cdot O_2 + O \rightarrow O_2^+ + O_3$	(3±2)[-10]	0	0		Chp. 18A
23.	$O_2^+ \cdot O_2 + NO \rightarrow NO^+ + O_2 + O_2$	(5)[-10]	0	0		Est.
24.	$O_2^+ \cdot O_2 + H_2O \rightarrow O_2^+ \cdot H_2O + O_2$	(1.5±0.5)[-9]	0	0		Chp. 18A
25.	$O_2^+ \cdot H_2O + O_2 \rightarrow O_2^+ \cdot O_2 + H_2O$	(2)[-10]	0	2300	$k_{300} = (9.4)[-14]$	Est.

Table 24-i. (Cont'd.)

No.	Reaction	σ	b	c	Notes	Sources
XIV.	Positive Ion-Atom Interchange (Cont'd.):					
26.	$O_2^+ \cdot H_2O \rightarrow NO \rightarrow NO^+ + O_2 + H_2O$	(1)[-10]	0	0		Est.
27. a.	$O_2^+ \cdot H_2O + H_2O \rightarrow H_3O^+ + OH + O_2$	(2.0 \pm 1.0)[-10]	0	0		Chp. 18A
b.	$\rightarrow H_3O^+ \cdot OH + O_2$	(1.0 \pm 0.4)[-9]	0	0		
28.	$NO^+ \cdot NO + H_2O \rightarrow NO^+ \cdot H_2O + NO$	(1.4 \pm 0.3)[-9]	0	0		Ref. 24-14
29.	$NO^+ \cdot H_2O + NO \rightarrow NO^+ \cdot NO + H_2O$	(2)[-10]	0	2300	$k_{300} = (9.4)[-14]$	
30.	$NO^+ (H_2O)_3 + H_2O$ $\rightarrow H_3O^+ (H_2O)_2 + HNO_2$	(7 \pm 2)[-11]	0	0		Chp. 18A
31.	$NO^+ \cdot CO_2 + H_2O$ $\rightarrow NO^+ \cdot H_2O + CO_2$	(1.0 \pm 0.3)[-9]	0	0		
32.	$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$	(1.8 \pm 0.3)[-9]	0	0		
33.	$H_3O^+ \cdot OH + H_2O$ $\rightarrow H_3O^+ \cdot H_2O + OH$	(1.4 \pm 0.5)[-9]	0	0		Ref. 24-15
34.	$C^+ + O_2 \rightarrow CO^+ + O$	(1.1 \pm 0.3)[-9]	0	0		
35.	$C^+ + CO_2 \rightarrow CO^+ + CO$	(1.8 \pm 0.6)[-9]	0	0		

Table 24-1. (Cont'd.)

No.	Reaction	σ	b	c	Notes	Sources
XIV.	Positive Ion-Atom Interchange (Cont'd.):					
36.	$\text{CO}_2^+ + \text{O} \rightarrow \text{CO} + \text{O}_2^+$	$(1.6 \pm 0.8)[-10]$	0	0	Cf. Reaction XIII.34.	Chp. 18A
37.	$\text{Fe}^+ + \text{O}_3 \rightarrow \text{FeO}^+ + \text{O}_2$	$(1.5 \pm 0.8)[-10]$	0	0		
38.	$\text{S}^+ + \text{O}_2 \rightarrow \text{SO}^+ + \text{O}$	$(1.6 \pm 0.3)[-11]$	0	0		
39.	$\text{U}^+ + \text{O}_2 \rightarrow \text{UO}^+ + \text{O}$	$(8.5^{+4.0}_{-1.0})[-10]$	0	0	$k < (1)[-11]$. Not detected for kinetic energies < 5 eV.	
40.	$\text{U}^+ + \text{N}_2 \rightarrow \text{UN}^+ + \text{N}$	-	-	-		Est.
41.	$\text{U}^+ + \text{NO} \rightarrow \text{UO}^+ + \text{N}$	$(1) \begin{bmatrix} +0 \\ -9 \\ -1 \end{bmatrix}$	0	0		
XV.	Negative-Ion Charge Transfer:					
1.	$\text{O}^- + \text{O}_2(\text{o}^1\Delta_g) \rightarrow \text{O}_2^- + \text{O}$	-	-	-	$k_{300} < (1)[-10]$. Cf. Reaction XII.3	Est.
2.	$\text{O}^- + \text{O}_3 \rightarrow \text{O} + \text{O}_3^-$	$(5.3 \pm 2.0)[-10]$	0	0	See Reaction XII.4.	Chp. 18A
3.	$\text{O}^- + \text{NO}_2 \rightarrow \text{O} + \text{NO}_2^-$	$(1.2 \pm 0.4)[-9]$	0	0		
4.	$\text{O}_2^- + \text{O} \rightarrow \text{O}_2 + \text{O}^-$	-	-	-	$k < (1)[-10]$	Est.
5.	$\text{O}_2^- + \text{O}_3 \rightarrow \text{O}_2 + \text{O}_3^-$	$(4.0 \pm 1.3)[-10]$	0	0		Chp. 18A
6.	$\text{O}_2^- + \text{NO}_2 \rightarrow \text{O}_2 + \text{NO}_2^-$	$(8 \pm 3)[-10]$	0	0		

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XV.	Negative-Ion Charge Transfer (Cont'd.):					
7.	$O_2^- + NO_3 \rightarrow O_2 + NO_3^-$	(5)[-10]	0	0		Est.
8.	$O_3^- + NO_2 \rightarrow O_3 + NO_2^-$	(2.8±1.0)[-10]	0	0	Products uncertain; cf. Reaction XVI. 5.	Chp. 18A
9.	$O_3^- + NO_3 \rightarrow O_3 + NO_3^-$	(5)[-10]	0	0		Est.
10.	$NO^- + O_2 \rightarrow NO + O_2^-$	(5±2)[-10]	0	0		Chp. 18A
11.	$NO_2^- + NO_3 \rightarrow NO_2 + NO_3^-$	(5)[-10]	0	0		Est.
12.	$O_2 \cdot H_2O + O_3 \rightarrow$ Products	(3.0±1.0)[-10]	0	0		Chp. 18A
13.	$O_2^-(H_2O)_2 + O_3 \rightarrow$ Products	(3.4±1.0)[-10]	0	0		
14.	$H^- + NO_2 \rightarrow H + NO_2^-$	(2.9±1.0)[-9]	0	0		
15.	$OH^- + NO_2 \rightarrow OH + NO_2^-$	(1.0±0.3)[-9]	0	0		
XVI.	Negative Ion-Atom Interchange:					
1.	$O^- + N_2O \rightarrow NO^- + NO$	(2.3±0.5)[-10]	0	0		Chp. 18A
2.	$O_3^- + O \rightarrow O_2^- + O_2$	(1) ⁺ [-11] -2]	0	0	No experimental data.	Est.
3.	$O_3^- + N_2 \rightarrow N_2O^- + O_2$	-	-	-	k<(1)[-15]	Chp. 18A

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XVI.	Negative Ion-Atom Interchange (Cont'd.):					
4.	$\text{O}_3^- + \text{NO} \rightarrow \text{NO}_2^- + \text{O}_2$	(1.0±0.3)[-11]	0	0	Ref. 18A-27 identifies products as $\text{NO}_3^- + \text{O}$. This is probably incorrect.	Chp. 18A
5.	$\text{O}_3^- + \text{NO}_2 \rightarrow \text{NO}_3^- + \text{O}_2$	(2±1)[-11]	0	0	Products uncertain; cf. Reaction XV.8.	Est.
6.	$\text{O}_3^- + \text{CO}_2 \rightarrow \text{CO}_3^- + \text{O}_2$	(4.0±1.2)[-10]	0	0		
7.	$\text{O}_3^- + \text{H} \rightarrow \text{OH}^- + \text{O}_2$	(8.4±4.0)[-10]	0	0		
8.	$\text{NO}_2^- + \text{O} \rightarrow \text{Products}$	-	-	-	$k < (1)[-11]$	
9.	$\text{NO}_2^- + \text{N} \rightarrow \text{Products}$	-	-	-	$k < (1)[-11]$	
10.	$\text{NO}_2^- + \text{O}_3 \rightarrow \text{O}_2 + \text{NO}_3^-$	(1.8±0.6)[-11]	0	0		
11.	$\text{NO}_2^- + \text{NO}_2 \rightarrow \text{NO}_3^- + \text{NO}$	(4.0±1.2)[-12]	0	0	Reverse Reactions (XVI.14, 15) important.	Chp. 18A
12.	$\text{NO}_3^- + \text{O} \rightarrow \text{Products}$	-	-	-	$k < (1)[-11]$	
13.	$\text{NO}_3^- + \text{N} \rightarrow \text{NO}_2^- + \text{NO}$	-	-	-	$k < (1)[-11]$	
14.	$\text{NO}_3^- + \text{NO} \rightarrow \text{NO}_2^- + \text{NO}_2$	-	-	-	$k < (1)[-12]$. See Reactions XVI.11, 15.	
15.	$\text{OONO}^- + \text{NO} \rightarrow \text{NO}_2^- + \text{NO}_2$	(1.5)[-11±1]	0	0	See Reactions XVI.11, 14.	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XVI. Negative Ion-Atom Interchange (Cont'd.):						
16.	$\text{O}_2^-\cdot\text{O}_2 + \text{O} \rightarrow \text{O}_3^- + \text{O}_2$	(4±2)[-10]	0	0	$2\text{O}_2 + \text{O}^-$ may be a minor product channel.	Chp. 18A
17.	$\text{O}_2^-\cdot\text{O}_2 + \text{NO} \rightarrow \text{OONO}^- + \text{O}_2$	(2.5±0.8)[-10]	0	0		
18.	$\text{O}_2^-\cdot\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{O}_2^-\cdot\text{H}_2\text{O} + \text{O}_2$	(1.4±0.4)[-9]	0	0		
19.	$\text{O}_2^-\cdot\text{O}_2 + \text{CO}_2 \rightarrow \text{CO}_4^- + \text{O}_2$	(4.3±1.3)[-10]	0	0		
20.	$\text{O}_2^-\cdot\text{H}_2\text{O} + \text{NO} \rightarrow \text{OONO}^- + \text{H}_2\text{O}$	(3.1±1.0)[-10]	0	0		
21.	$\text{O}_2^-\cdot\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{CO}_4^- + \text{H}_2\text{O}$	(5.8±1.0)[-10]	0	0		
22.	$\text{CO}_3^- + \text{O} \rightarrow \text{O}_2^- + \text{CO}_2$	(8.0±2.4)[-11]	0	0	See Reaction XII. 14.	
23.	$\text{CO}_3^- + \text{NO} \rightarrow \text{NO}_2^- + \text{CO}_2$	(9.0±3.0)[-12]	0	0		
24.	$\text{CO}_3^- + \text{NO}_2 \rightarrow \text{NO}_3^- + \text{CO}_2$	(8.0±3.0)[-11]	0	0		
25.	$\text{CO}_4^- + \text{O} \rightarrow \text{CO}_3^- + \text{O}_2$	(1.5±0.8)[-10]	0	0	$\text{CO}_2 + \text{O}_3^-$ may be a minor product channel.	
26.	$\text{CO}_4^- + \text{O}_2 \rightarrow \text{O}_4^- + \text{CO}_2$	(4.3)[-10]	0	3000	$k_{300} = (2.0)[-14]$	Est.
27.	$\text{CO}_4^- + \text{NO} \rightarrow \text{OONO}^- + \text{CO}_2$	(4.8±2.0)[-11]	0	0		Chp. 18A

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XVII. Radiation-Stabilized Positive-Ion-Neutral Association:						
1.	$X^+ + Y \rightleftharpoons (XY)^{++} \rightarrow XY^+ + h\nu$	$\left\{ \begin{array}{l} (1) [-2.0 \pm 0.5] \\ (1) [-15.0 \pm 0.5] \\ (1) [-13.0 \pm 0.5] \end{array} \right\}$	$\left\{ \begin{array}{l} 0 \\ 0 \\ 0 \end{array} \right\}$	$\left\{ \begin{array}{l} 0 \\ 0 \\ 0 \end{array} \right\}$	$\left\{ \begin{array}{l} \text{Monatomic reactants} \\ \text{Diatomic reactants} \\ \text{Polyatomic reactants} \\ \text{and complex reactants} \end{array} \right\}$ Est.	
XVIII. Positive-Ion Photodissociation:						
Reactions of this type are not currently considered relevant to problems involving atmospheric chemical recovery following a perturbation (Ref. 24-2). Nevertheless, this section of the table is reserved pending any future change in the situation.						
XIX. Three-Body Positive-Ion-Neutral Association:						
1.	$O^+ + N_2 + M \rightarrow NO^+ + N + M$	(5.4)[-29]	$\begin{pmatrix} +0.5 \\ -1.0 \\ -1.0 \end{pmatrix}^g$	0	$T_{ref} = 82 \text{ K}; M = He;$ Apparently N_2O pre-dissociates.	Chp. 18A
2.	$N^+ + N_2 + M \rightarrow N_3^+ + M$	(1.8±0.2)[-29]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$M = N_2$	Refs. 24-16, 24-17.
3.	$O_2^+ + O_2 + M \rightarrow O_4^+ + M$	(2.8)[-30]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$T_{ref} = 307 \text{ K}; M = O_2.$	Chp. 18A
4.	$O_2^+ + N_2 + M \rightarrow O_2^+ \cdot N_2 + M$	(8±4)[-31]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$T_{ref} = 200 \text{ K}; M = He.$	
5.	$O_2^+ + H_2O + M \rightarrow O_2^+ \cdot H_2O + M$	(1.9)[-28]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$T_{ref} = 296 \text{ K}; M = O_2.$	
6.	$N_2^+ + N_2 + M \rightarrow N_4^+ + M$	(5.0)[-29]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$M = N_2$	
7.	$NO^+ + N_2 + M \rightarrow NO^+ \cdot N_2 + M$	(2)[-31]	$\begin{pmatrix} -1.0 \\ +0.5 \\ -1.0 \end{pmatrix}^g$	0	$M = NO$	

Note:

^g Value of "b" estimated (Ref. 24-12).

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIX. Three-Body Positive-Ion-Neutral Association (Cont'd.):						
8.	$\text{NO}^+ + \text{NO} + \text{M} \rightarrow \text{NO}^+ \cdot \text{NO} + \text{M}$	(5.0)[-30]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = NO	Chp. 18A
9.	$\text{NO}^+ + \text{H}_2\text{O} + \text{M} \rightarrow \text{NO}^+ \cdot \text{H}_2\text{O} + \text{M}$	(1.5)[-28]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = N ₂	
10a.	$\text{NO}^+ + \text{CO}_2 + \text{M} \rightarrow \text{NO}^+ \cdot \text{CO}_2 + \text{M}$	(3)[-29]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	T _{ref} = 200 K; M = N ₂	
b.		(2)[-29]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = CO ₂	
11.	$\text{NO}^+ \cdot \text{H}_2\text{O} + \text{H}_2\text{O} + \text{M}$ $\quad - \text{NO}^+(\text{H}_2\text{O})_2 + \text{M}$	(1.1)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = N ₂	
12.	$\text{NO}^+(\text{H}_2\text{O})_2 + \text{H}_2\text{O} + \text{M}$ $\quad - \text{NO}^+(\text{H}_2\text{O})_3 + \text{M}$	(1.6)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = N ₂	
13.a.	$\text{H}_3\text{O}^+ + \text{H}_2\text{O} + \text{M} \rightarrow \text{H}_3\text{O}^+ \cdot \text{H}_2\text{O} + \text{M}$	(3.7)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	T _{ref} = 307 K; M = O ₂	
b.		(3.4)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = N ₂	
14.a.	$\text{H}_3\text{O}^+ \cdot \text{H}_2\text{O} + \text{H}_2\text{O} + \text{M}$ $\quad - \text{H}_3\text{O}^+(\text{H}_2\text{O})_2 + \text{M}$	(2.0)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	T _{ref} = 307 K; M = O ₂	
b.		(2.3)[-27]	$(-1.0^{+0.5})^g$ $(-1.0^{-1.0})$	0	M = N ₂	
Note: g Value of "b" estimated (Ref. 24-12).						

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XIX. Three-Body Positive-Ion-Neutral Association (Cont'd.):						
15. a.	$\text{H}_3\text{O}^+(\text{H}_2\text{O})_2 + \text{H}_2\text{O} + \text{M}$ $- \text{H}_3\text{O}^+(\text{H}_2\text{O})_3 + \text{M}$	(2.0)[-27]	$(-1.0^{+0.5}_{-1.0})^g$	0	$T_{\text{ref}} = 307 \text{ K}; \text{M} = \text{O}_2$	Chp. 18A
b.		(2.4)[-27]	$(-1.0^{+0.5}_{-1.0})^g$	0	$\text{M} = \text{N}_2$	
16.	$\text{H}_3\text{O}^+(\text{H}_2\text{O})_3 + \text{H}_2\text{O} + \text{M}$ $- \text{H}_3\text{O}^+(\text{H}_2\text{O})_4 + \text{M}$	(9.0)[-28]	$(-1.0^{+0.5}_{-1.0})^g$	0	$T_{\text{ref}} = 307 \text{ K}; \text{M} = \text{O}_2$	
XX. ^h Positive-Ion Collisional Dissociation:						
1.	$\text{O}_2^+ \cdot \text{O}_2 + \text{M} - \text{O}_2^+ + \text{O}_2 + \text{M}$	(2.4 ± 1.2)[-6]	(-1)	4900	$k_{300} = (2.0 \pm 1.0)[-13];$ $\text{M} = \text{O}_2$	Refs. 24-18 through 24-20
2.	$\text{NO}^+ \cdot \text{NO} + \text{M} - \text{NO}^+ + \text{NO} + \text{M}$	(4)[-5 ± 1]	(-1)	7300 ± 1000	$k_{300} = (9 \pm 2)[-16];$ $\text{M} = \text{NO}$	Refs. 24-14, 24-21
3.	$\text{H}_3\text{O}^+ \cdot \text{OH} + \text{M} - \text{H}_3\text{O}^+ + \text{OH} + \text{M}$	(3)[-3 ± 2]	(-1)	12,000	$k_{300} = (1)[-20];$ bond- ing energy lies be- tween 0.77 and 1.52 eV.	Refs. 24-2, 24-22 + Est.
4.	$\text{H}_3\text{O}^+ \cdot \text{H}_2\text{O} + \text{M} - \text{H}_3\text{O}^+ + \text{H}_2\text{O} + \text{M}$	(8.8 ± 1.3)[0]	(-1)	18,000	$k_{300} \approx (7)[-26];$ $\text{M} = \text{N}_2$	Refs. 24-23, 24-24
Notes:						
^g Value of "b" estimated (Ref. 24-12).						
^h In this section, the "a" parameters have been obtained by back-calculation from measured or estimated values of "c" and of the rate constant at or very near 300 K, i.e., k_{300} , as referenced. The "b" parameter has been uniformly estimated as equal to (-1) (Ref. 24-2).						

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
<u>XX. Positive-Ion Collisional Dissociation (Cont'd.):</u>						
5.	$\text{H}_3\text{O}^+(\text{H}_2\text{O})_2 + \text{M}$ $-\text{H}_3\text{O}^+ \cdot \text{H}_2\text{O} + \text{H}_2\text{O} + \text{M}$	(8.0±3.2) -2	(-1)	11,000	$k_{300} = (1.0 \pm 0.4) -17 $; $\text{M} = \text{N}_2, \text{O}_2$.	Refs. 24-23 through 24-25
6.	$\text{H}_3\text{O}^+(\text{H}_2\text{O})_3 + \text{M}$ $-\text{H}_3\text{O}^+(\text{H}_2\text{O})_2 + \text{H}_2\text{O} + \text{M}$	(5.0 ^{+5.0} _{-2.5}) -2	(-1)	8600	$k_{300} = (2^{+2}) -14 $; $\text{M} = \text{N}_2, \text{O}_2, \text{NO}$.	Refs. 24-14, 24-23 through 24-25
7.	$\text{H}_3\text{O}^+(\text{H}_2\text{O})_4 + \text{M}$ $-\text{H}_3\text{O}^+(\text{H}_2\text{O})_3 + \text{H}_2\text{O} + \text{M}$	(7.6±1.2) -1	(-1)	7700	$k_{300} = (6) -12 $; $\text{M} = \text{O}_2$	Refs. 24-24, 24-25
<u>XXI. Radiation-Stabilized Negative-Ion-Neutral Association:</u>						
1.	$\text{O}^- + \text{O}_2 \rightarrow \text{O}_3^- + h\nu$	(1) -17±2	0	0		Est.
<u>XXII. Negative-Ion Photodissociation:</u>						
1.	$\text{O}_2^- \cdot \text{O}_2 + h\nu \rightarrow \text{O}_2^- + \text{O}_2$	(2)(0±3)	0	0	Cf. Reaction VIII.4. ⁱ	Ref. 24-6
<u>XXIII. Three-Body Negative-Ion-Neutral Association:</u>						
1.	$\text{O}^- + \text{O}_2 + \text{M} \rightarrow \text{O}_3^- + \text{M}$	(1.1±0.1) -30	(-1 ^{+0.5} _{-1.0}) ^g	0	$\text{M} = \text{O}_2$	Chp. 18A
Notes:						
^g Value of "b" estimated (Ref. 24-12).						
^h In this section, the "a" parameters have been obtained by back-calculation from measured or estimated values of "c" and of the rate constant at or very near 300 K, i.e., k_{300} , as referenced. The "b" parameter has been uniformly estimated as equal to (-1) (Ref. 24-2).						
ⁱ Reactions VIII.4 and XXII.1 are probably indistinguishable, but XXII.1 is thought to dominate (Ref. 24-26).						

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXIII. Three-Body Negative-Ion-Neutral Association (Cont'd.):						
2.	$O^- + N_2 + M \rightarrow N_2O^- + M$	(3)[-31]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$T_{ref} = 200 \text{ K}; M = He.$	Chp. 18A
3.	$O^- + NO + M \rightarrow NO_2^- + M$	(1)[-29±2]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	Reaction XI.7 is dominant.	Est.
4.	$O^- + H_2O + M \rightarrow O^- \cdot H_2O + M$	(1.0)[-28]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	Chp. 18A
5.	$O^- + CO_2 + M \rightarrow CO_3^- + M$	(8.0)[-29]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = CO_2$	
6.	$O_2^- + O_2 + M \rightarrow O_4^- + M$	(3.5±0.5)[-31]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	
7.	$O_2^- + N_2 + M \rightarrow O_2^- \cdot N_2 + M$	(3)[-32]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$T_{ref} = 200 \text{ K}; M = He.$	
8.	$O_2^- + H_2O + M \rightarrow O_2^- \cdot H_2O + M$	(3)[-28]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	
9.	$O_2^- + CO_2 + M \rightarrow CO_4^- + M$	(2.0)[-29]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	
10.	$O_3^- + H_2O + M \rightarrow O_3^- \cdot H_2O + M$	(2.1)[-28]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	Chp. 18A
11.	$NO_2^- + H_2O + M \rightarrow NO_2^- \cdot H_2O + M$	(1.3)[-28]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = NO$	
12.	$O_2^- \cdot H_2O + H_2O + M \rightarrow O_2^-(H_2O)_2 + M$	(4)[-28]	$\begin{pmatrix} +0.5^g \\ -1.0 \\ -1.0 \end{pmatrix}$	0	$M = O_2$	
XXIV. Negative-Ion Collisional Dissociation:						
1.	$O_2^- \cdot O_2 + M \rightarrow O_2^- + O_2 + M$	(2.0±1.2)[-5]	(-1)	6300	$k_{300} = (1.7 \pm 1.0)[-14]; M = O_2.$	Refs. 24-27 through 24-30.

Notes:

g Value of "b" estimated (Ref. 24-12).

j See Footnote "h".

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
<u>XXV. Radiation-Stabilized Neutral Recombination:</u>						
1.a.	$O + O - O_2(A^3\Sigma_u^+)^- \rightarrow O_2 + h\nu$ (Herzberg)	(2.4±0.1) (-21)	0	0		Refs. 24-31, 24-32
b.	$-O_2(b^1\Sigma_g^+)^- \rightarrow O_2 + h\nu$ (Atmospheric)	(1.7±0.2) (-37) $\cdot n_{N_2}$	0	0		Ref. 24-32
c.	$-O_2(B^3\Sigma_u^-)^- \rightarrow O_2 + h\nu$ (Schumann-Runge)	(2) (-17)	0	12,000±1100	$k_{300} = (8.5) (-35)$	Ref. 24-33
2.a.	$O + N - NO(A^2\Sigma^+)^- \rightarrow NO + h\nu$ (gamma)	$\left\{ 1.2 \times 10^{-17} \left(\frac{T}{300} \right)^{-0.35} + 2.1 \times 10^{-34} n_{N_2} \left(\frac{T}{300} \right)^{-1.24} \right\}$				} Ref. 24-34
b.	$-NO(B^2\Pi)^- \rightarrow O + h\nu$ (beta)	(3.1±0.1) (-34) $\cdot n_{N_2}$	(-1.4)	0		
c.	$-NO(C^2\Pi)^- \rightarrow NO + h\nu$ (delta)	(6.8±3.0) (-18)	(-0.35)	0		
3.	$O + NO - NO_2 + h\nu$	(8±2) (-17)	(-2.0±0.5)	0	$p \geq 0.3$ torr	} Chp. 19
4.	$N + N - N_2 + h\nu$	(7±2) (-18)	(-2.0±0.5)	0	$p \leq 10^{-3}$ torr	
		(1.0±0.5) (-17)	(-0.90±0.05)	0		Ref. 24-35
<u>XXVI. Neutral Photodissociation:</u>						
1.a.	$O_2 + h\nu \rightarrow O + O$				} Flux and wave-length dependent. See Chp. 12.	
b.	$-O + O(^1D)$ (Schumann-Runge)					
2.	$NO + h\nu \rightarrow N + O$					

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXVI. <u>Neutral Photodissociation (Cont'd.):</u>						
3.a.	$O_3 + h\nu \rightarrow O + O_2$					
b.	$\rightarrow O + O_2(^1\Delta_g)$					
c.	$\rightarrow O(^1D) + O_2(^1\Delta_g)$					
d.	$\rightarrow O(^1D) + O_2(^1\Sigma_g)$					
4.	$NO_2 + h\nu \rightarrow O + NO$					
5.a.	$N_2O + h\nu \rightarrow N_2 + O$					
b.	$\rightarrow N + NO$					
6.	$OH + h\nu \rightarrow O + H$					
7.	$H_2O + h\nu \rightarrow H + OH$					
8.	$HO_2 + h\nu \rightarrow OH + O$					
9.	$H_2O_2 + h\nu \rightarrow OH + OH$					
10.	$CO_2 + h\nu \rightarrow CO + O$					
XXVII. <u>Three-Body Neutral Recombination:</u>						
1.	$O + O + O \rightarrow O_2 + O(^1S)$	(1.5) [-34±1]	0	0		
2.	$O + O + O_2 \rightarrow O_2(^3\Sigma_u^+) + O_2$	(3) [-33.0±0.3]	0	0	T = 1000 K	Chp. 20

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXVII. Three-Body Neutral Recombination (Cont'd.):						
3.a.	$O + O + N_2 \rightarrow O_2 + N_2$	(3.0)[-33]	(-2.9±0.4)	0	$T_{ref} = 3000\text{ K}$	Chp. 19
b.	$\rightarrow O_2(A^3\Sigma_u^+) + N_2$	(3.9)[-34]	(-2.5±0.5)	0		Chp. 20
c.	$\rightarrow O_2(b^1\Sigma_g^+) + N_2$	(2.1)[-37±1]	0	0		
		(1.7)[-37±1]	0	0		
4.a.	$N + N + N_2 \rightarrow N_2 + N_2$	(7.6±2.0)[-34]	0	-500±200	$k_{300} = (4.0)[-33]$	Chp. 19
b.	$\rightarrow N_2 + N_2(8^3\Pi)$	(4.6±0.2)[-33]	(-1.7)	0	$T_{ref} = 3000\text{ K}$	Chp. 20
		(1.4)[-33±1]	0	0		
5.	$N + O + O \rightarrow NO + O(^1S)$	(3)[-33±1]	0	0		Chp. 19
6.	$N + O + N_2 \rightarrow NO + N_2$	(1.1±0.3)[-32]	(-0.5±0.2)	0		Chp. 20
7.	$N + O + N_2 \rightarrow NO(8^2\Pi) + N_2$	(1)[-34±1]	0	0		Chp. 19
8.	$O + O_2 + N_2 \rightarrow O_3 + N_2$	(1.1)[-34]	0	-510±200	$k_{300} = (6.0)[-34]$	Est.
9.	$O + N_2 + M \rightarrow N_2O + M$	(1)[-34±2]	0	7500	$k_{300} = (1.4)[-45]$	Chp. 19
10.	$O + NO + N_2 \rightarrow NO_2 + N_2$	(1.0±0.1)[-31]	(-2.5±0.3)	0		Ref. 24-36
11.	$H + H + M \rightarrow H_2 + M$	(8.3)[-33.0±0.5]	(-0.6±0.2)	0		Chp. 19
12.	$H + O_2 + N_2 \rightarrow HO_2 + N_2$	(2.1±0.4)[-32]	0	-300±100	$k_{300} = (5.5)[-32]$	Chp. 19

Table 24-1. (Cont'd.)

No.	Reaction	σ	b	c	Notes	Sources
<u>XXVI. Three-Body Neutral Recombination (Cont'd.):</u>						
13.	$H + OH + M \rightarrow H_2O + M$	$(7 \pm 4)[-32]$	0	0	$T = 2000 \text{ K}$	Ref. 24-37
14.	$CO + O + N_2 \rightarrow CO_2 + N_2$	$(1.4 \pm 0.3)[-35]$	0	0		Ref. 24-38
<u>XXVIII. Neutral Collisional Dissociation:</u>						
1.	$O_2 + O_2 \rightarrow O + O + O_2$	$(2.1 \pm 1.0)[-7]$	(-1.5 ± 0.5)	59,000	$T = 3000-5000 \text{ K}$	Ref. 24-33
2.	$N_2 + N_2 \rightarrow N + N + N_2$	$(6.7 \pm 1.7)[-7]$	(-1.6 ± 0.5)	113,000	$T = 8000-15,000 \text{ K}$	} Ref. 24-39
3.	$N_2 + Ar \rightarrow N + N + Ar$	$(2.5 \pm 0.3)[-7]$	(-1.6 ± 0.5)	113,000	$T = 8000-15,000 \text{ K}$	
4.	$NO + M \rightarrow N + O + M$	$(1.3 \pm 0.6)[-7]$	(-1.5 ± 0.5)	75,000	$T = 3000-8000 \text{ K};$ $M = Ar, O_2, N_2$	Ref. 24-40
5.	$O_3 + O_2(a^1\Delta_g) \rightarrow O + O_2 + O_2$	$(4.5)[-11]$	0	2800 ± 200	$T = 283-321 \text{ K};$ $k_{300} = (4)[-15]$	Ref. 24-41
6.	$O_3 + O_2(b^1\Sigma_g^+) \rightarrow O + O_2 + O_2$	$(2.5 \pm 0.5)[-11]$	0	0		Ref. 24-42
7.	$O_3 + N_2 \rightarrow O + O_2 + N_2$	$(6.4 \pm 1.6)[-10]$	0	11,400	$T = 200-1000 \text{ K};$ $k_{300} = (2)[-26]$	Ref. 24-43
<u>XXIX. Neutral Rearrangement:</u>						
1.	$O + N_2 \rightarrow NO + N$	$(1.0 \pm 0.3)[-10]$	0	$37,900 \pm 300$	$k_{300} = (1.1)[-65]$	} Chp. 19
2.	$O + NO \rightarrow O_2 + N$	$(5.3 \pm 1.1)[-12]$	0	$20,200 \pm 200$	$k_{300} = (3.1)[-41]$	
3.	$O + O_3 \rightarrow O_2 + O_2$	$(1.5 \pm 0.3)[-11]$	0	2240 ± 200	$k_{300} = (8.0)[-15]$	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXIX.	Neutral Rearrangement (Cont'd.):					
4.	$O(^1D) + O_3 \rightarrow O_2 + O_2$	$(2.5 \pm 1.0)[-10]$	0	0		Ref. 24-42
5.	$O + NO_2 \rightarrow NO + O_2$	$(9.1 \pm 2.0)[-12]$	0	0		Chp. 19
6.a.	$O + N_2O \rightarrow NO + NO$	$(1.5 \pm 0.5)[-10]$	0	$14,000 \pm 2000$	$k_{700} = (7.8)[-31]$	
b.	$\rightarrow O_2 + N_2$	$(5 \pm 2)[-11]$	0	$14,000 \pm 2000$	$k_{300} = (2.6)[-31]$	
7.	$O(^1D) + H_2 \rightarrow OH + H$	$(3.5)[-10 \pm 1]$	0	0		Ref. 24-44
8.	$O + OH \rightarrow H + O_2$	$(5 \pm 2)[-11]$	0	0	Possibly $b = 0.5$	Chp. 19
9.	$O + HO_2 \rightarrow OH + O_2$	-	-	-	$k \approx (1)[-11]$	Chp. 19 + Est.
10.	$O(^1D) + H_2O \rightarrow OH + OH$	$(2 \pm 1)[-10]$	0	0		Ref. 24-45
11.	$N + O_2 \rightarrow NO + O$	$(2.4 \pm 0.3)[-11]$	0	4000 ± 200	$k_{300} = (3.9)[-17]$	Chp. 19
12.	$N(^2D) + O_2 \rightarrow NO + O$	$(7.0 \pm 0.1)[-12]$	(0.5)	0		Chp. 20
13.	$N + O_2(^1\Delta_g) \rightarrow NO + O$	$(2.0 \pm 0.8)[-14]$	0	600	Products uncertain; $k_{300} = (2.7)[-15]$	Ref. 24-46
14.	$N + NO \rightarrow N_2^+ (v = 3-6) + O$	$(2.2 \pm 0.6)[-11]$	0	0		Chps. 19, 20
15.	$N + O_3 \rightarrow NO + O_2$	$(3.1 \pm 0.8)[-11]$	(0.5)	1200	$k_{300} = (5.7)[-13]$	Ref. 24-47

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
<u>XXIX. Neutral Rearrangement (Cont'd.):</u>						
16. a.	$N + NO_2 \rightarrow N_2O + O$	$(8 \pm 1)[-12]$	0	$\left. \begin{array}{l} 0 \\ 0 \\ 0 \\ 0 \end{array} \right\}$	Chp. 19 gives $\alpha = (1.8 \pm 0.2)[-11]$ for overall reaction: $N + NO_2 \rightarrow \text{Products}$	Ref. 24-48 gives branching ratio.
b.	$\rightarrow NO + NO$	$(6 \pm 1)[-12]$	0			
c.	$\rightarrow N_2 + O + O$	$(2 \pm 1)[-12]$	0			
d.	$\rightarrow N_2 + O_2$	$(2 \pm 1)[-12]$	0			
17.	$NO + O_2 \rightarrow NO \rightarrow NO_2 + NO_2$	$(6.6 \pm 3.3)[-39]$	0	-526	$k_{300} = (3.8)[-38]$	Ref. 24-49
18.	$NO + O_3 \rightarrow NO_2 + O_2$	$(9.5 \pm 1.0)[-13]$	0	1300 ± 100	$k_{300} = (1.3)[-14]$	Chp. 19
19. a.	$NO_2 + O_3 \rightarrow NO_3 + O_2$ $\rightarrow NO + O_2 + O_2$	$(9.8)[-12]$	0	3500 ± 300	Values given are for the overall reaction: $NO_2 + O_3 \rightarrow \text{Products};$ $k_{300} = (8.5)[-17]$.	Ref. 24-50
b.						
20. a.	$H + O_3 \rightarrow OH + O_2$	$(2.6 \pm 0.5)[-11]$	0	0		Ref. 24-51
b.	$\rightarrow HO_2 + O$					
21.	$H + OH \rightarrow H_2 + O$	$(1.2 \pm 0.4)[-11]$	0	3650	$k_{300} = (6.3)[-17]$	Ref. 24-37
22. a.	$H + HO_2 \rightarrow OH + OH$	$(4.2)[-10.6 \pm 0.3]$	0	950	$k_{300} = (1.8)[-11]$	Ref. 24-52
b.	$\rightarrow H_2 + O_2$	$(4.2)[-11.0 \pm 0.4]$	0	350	$k_{300} = (1.3)[-11]$	
23.	$H + H_2O_2 \rightarrow H_2 + HO_2$	$(2.8)[-12.0 \pm 0.3]$	0	1900	$k_{300} = (5.0)[-15]$	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXIX. Neutral Rearrangement (Cont'd.):						
24.	$\text{OH} + \text{O}_3 \rightarrow \text{HO}_2 + \text{O}_2$	$(1.3 \pm 0.4) \times 10^{-12}$	0	950	$k_{300} = (5.5) \times 10^{-14}$	Ref. 24-53
25.	$\text{OH} + \text{OH} \rightarrow \text{H}_2\text{O} + \text{O}$	$(4.9 \pm 0.8) \times 10^{-11}$	0	400	$k_{300} = (1.3) \times 10^{-11}$	
26.	$\text{OH} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{H}$	$(3.6 \pm 1.3) \times 10^{-11}$	0	2590	$k_{300} = (6.4) \times 10^{-15}$	Ref. 24-37
27.	$\text{OH} + \text{HO}_2 \rightarrow \text{H}_2\text{O} + \text{O}_2$	-	-	-	$k_{300} = (1) \times 10^{-11}$	Ref. 24-54
28.	$\text{OH} + \text{H}_2\text{O}_2 \rightarrow \text{H}_2\text{O} + \text{HO}_2$	$(1.7 \pm 0.9) \times 10^{-11}$	0	910	$k_{300} = (8.2) \times 10^{-13}$	Ref. 24-52
29.	$\text{HO}_2 + \text{HO}_2 \rightarrow \text{H}_2\text{O}_2 + \text{O}_2$	$(3.3 \pm 0.7) \times 10^{-12}$	0	0		
30.	$\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}$	$(9.3 \pm 1.3) \times 10^{-13}$	0	540 ± 250	$k_{300} = (1.5) \times 10^{-13}$	Ref. 24-55
XXX. Radiative Electronic-State Deexcitation:						
1.	$\text{O}(^1\text{D}) \rightarrow \text{O} + h\nu$	$(6.8 \pm 2.0) \times 10^{-3}$	0	0		Chp. 20
2.	$\text{O}(^1\text{S}) \rightarrow \text{O} + h\nu$	$(1.35 \pm 0.40) \times 10^1$	0	0	Pressure-dependent	
3. a.	$\text{N}(^2\text{D})_{3/2} \rightarrow \text{N} + h\nu$	$(1.6) \times 10^{-5.0 \pm 0.3}$	0	0		
b.	$\text{N}(^2\text{D})_{1/2} \rightarrow \text{N} + h\nu$	$(7.1) \times 10^{-6.0 \pm 0.3}$	0	0		
4.	$\text{N}(^2\text{P}) \rightarrow \text{N} + h\nu$	$(7.7) \times 10^{-2.0 \pm 0.3}$	0	0		
5.	$\text{O}_2(^1\Delta_g) \rightarrow \text{O}_2 + h\nu$	$(2.6 \pm 1.0) \times 10^{-4}$	0	0	Pressure-dependent	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXX. Radiative Electronic-State Deexcitation (Cont'd.):						
6.	$O_2(^1\Sigma_g^+) - O_2 + h\nu$	(8.3)(-2.0±0.3)	0	0	Chp. 20	
7.a.	$N_2(A^3\Sigma_u^+)(F_2) - N_2 + h\nu$	(7.7)(-1.0±0.3)	0	0		
b.	$N_2(A^3\Sigma_u^+)(F_1, F_3) - N_2 + h\nu$	(3.7)(-1.0±0.3)	0	0		
8.	$NO(a^4\Pi) - NO + h\nu$	(6.3)(0.0±0.3)	0	0		
9.	$NO_2(^2B_1) - NO_2 + h\nu$	(1.4±0.2)(+4)	0	0		
10.a.	$O(^2D)_{5/2} - O^+ + h\nu$	(4.8)(-5.0±0.3)	0	0		
b.	$O(^2D)_{3/2} - O^+ + h\nu$	(1.7)(-4.0±0.3)	0	0		
11.a.	$O(^2P)_{3/2} - O^+ + h\nu$	(2.4)(-1.0±0.3)	0	0		
b.	$O(^2P)_{1/2} - O^+ + h\nu$	(1.9)(-1.0±0.3)	0	0		
12.	$N(^1D) - N^+ + h\nu$	(4.0)(-3.0±0.3)	0	0		
13.	$N(^1S) - N^+ + h\nu$	(1.1)(0.0±0.3)	0	0		
XXXI. Electronic State Photoexcitation:						
1.	$O_2 + h\nu - O_2(^1\Delta_g)$				(Flux and wavelength dependent)	
2.	$O_2 + h\nu - O_2(^b\Sigma_g^+)$					

Table 24-1. (Cont'd.)

No.	Reactor	σ	b	c	Notes	Sources
XXXII. Collisional Electronic State Quenching:						
1.	$O(^1D) + e - O(^3P) + e$	$(1.5) \times 10^{-11}$	0	0	For additional quenchants of $O(^1D)$, see Table 20-8.	Chp. 20
2.	$O(^1D) + O_2 - O + O_2(^1\Sigma_g^+)$	$(7 \pm 2) \times 10^{-11}$	0	0		Refs. 24-56, 24-57
3.	$O(^1D) + N_2 - O + N_2$	$(8.0 \pm 4.0) \times 10^{-11}$	0	0		Chp. 20
4.	$O(^1D) + CO_2 - O + CO_2$	$(3 \pm 1) \times 10^{-12}$	0	0		Ref. 24-56
5.a.	$O(^1S) + e - O(^3P) + e$	$(1.8) \times 10^{-11}$	0	0	Cf. Figure 20-9.	Chp. 20
b.	$- O(^1D) + e$	$(4) \times 10^{-11}$	0	0		Ref. 24-58
6.	$O(^1S) + O - O + O$	$(1.8 \pm 0.2) \times 10^{-13}$	0	0		Chp. 20
7.	$O(^1S) + O_2 - O + O_2$	$(3 \pm 1) \times 10^{-13}$	0	0	$k < (1) \times 10^{-17}$	Refs. 24-59 through 24-61
8.	$O(^1S) + N_2 - O + N_2$	-	-	-		Ref. 24-62
9.	$O(^1S) + H_2O - O + H_2O$	$(3 \pm 2) \times 10^{-10}$	0	0		Refs. 24-63, 24-64
10.	$O(^1S) + CO_2 - O + CO_2$	$(3.3 \pm 0.3) \times 10^{-13}$	0	0		Refs. 24-60, 24-61
11.	$O(^2D) + e - O^+ + e$	$(1) \times 10^{-7 \pm 2}$	0	0	$k \approx (6) \times 10^{-15}$	Ref. 24-65
12.	$N(^2D) + e - N + e$	$(5) \times 10^{-10 \pm 1}$	0	0		Chp. 20
13.	$N(^2D) + N_2 - N + N_2$	-	-	-		Ref. 24-60

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXXII. Collisional Electronic-State Quenching (Cont'd.):						
14. k	$O_2(a^1\Delta_g) + e \rightarrow O_2 + e$	(1)[-11±1]	0	0	Detailed balance calculation	Ref. 24-66 + Chp. 20 (Fig. 20-8) + Est.
15. k	$O_2(a^1\Delta_g) + O \rightarrow O_2 + O$	-	-	-	$k \approx (1)[-16]$	Chp. 20 (Table 20-6)
16. k	$O_2(a^1\Delta_g) + O_2 \rightarrow O_2 + O_2$	(2.4±0.2)[-18]	0	0		
17. k	$O_2(a^1\Delta_g) + O_2(a^1\Delta_g) \rightarrow O_2 + O_2(b^1\Sigma_g^+)$	(2)[-18±1]	0	0		Ref. 24-67
18. k	$O_2(a^1\Delta_g) + N_2 \rightarrow O_2 + N_2$	-	-	-	$k < (1.1)[-19]$	Chp. 20 (Table 20-6)
19. k	$O_2(a^1\Delta_g) + O_3 \rightarrow O_2 + O_3$	(3±2)[-15]	0	0		
20.	$O_2(b^1\Sigma_g^+) + O_2 \rightarrow O_2 + O_2$	(4.5±4.0)[-16]	0	0		Ref. 24-59
21.	$O_2(b^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2$	(2.0±1.0)[-15]	0	0		
22.	$N_2(A^3\Sigma) + O \rightarrow N_2 + O$	-	-	-	$k \approx (3)[-11]$	Chp. 20 (Table 20-4)
23.	$N_2(A^3\Sigma) + N \rightarrow N_2 + N$	(5)[-11 ⁺⁰ ₋₁]	0	0		
24.	$N_2(A^3\Sigma) + O_2 \rightarrow N_2 + O_2$	(3.8±2.0)[-12]	0	0		
Note: k For additional quenchants of $O_2(a^1\Delta_g)$, see Table 20-6.						

Table 24-1. (Cont'd.)

No.	Reaction	σ	b	c	Notes	Sources
XXXII. Collisional Electronic-State Quenching (Cont'd.):						
25.	$N_2(A^3\Sigma) + NO \rightarrow N_2 + NO$	(7±4) -11	0	0		Chp. 20 (Table 20-4)
26.	$N_2^+(A^2\Pi) + N_2 \rightarrow N_2^+ + N_2$	(1) -9±1	0	0		Chp. 20
27.	$N_2^+(B^2\Sigma) + O_2 \rightarrow N_2^+ + O_2$	(2) -9±1	0	0		
28.	$N_2^+(B^2\Sigma) + N_2 \rightarrow N_2^+ + N_2$	(6) -10±1	0	0		
XXXIII. Radiative Vibrational-State Deexcitation:						
1.	$CO(v=1) \rightarrow CO(v=0) + h\nu$	(3.3±0.3) +1	0	0		Chp. 11
2.	$CO_2(001) \rightarrow CO_2(000) + h\nu$	(4.00±0.20) +21	0	0		
XXXIV. Collisional Vibrational-State Quenching:						
1.	$O_2(v=1) + M \rightarrow O_2(v=0) + M$	$\left\{ \frac{2.5 \times 10^{-12} T \exp[-(2.95 \times 10^6/T)]}{(1 - e^{-2270/T})} \right\}^{1/3}$			$M = N_2 \text{ or } O_2$ $T = 800-3200 \text{ K}$	Chp. 20 (Table 20-5)
2.	$O_2(v=1) + O \rightarrow O_2(v=0) + O$	(5.7±3.0) -12 (1.7±0.5) -10	(-0.5) 0	483 4000	$T = 300-1700 \text{ K}$ $k_{300} = (i.) -12 $ $T = 2000-4000 \text{ K}$	
3.	$N_2(v=1) + O \rightarrow N_2(v=0) + O$	$\left\{ \frac{6.21 \times 10^{-14} T \exp[-(1.37 \times 10^5/T)]}{(1 - e^{-3390/T})} \right\}^{1/3}$ $\left\{ \frac{3.43 \times 10^{-12} T \exp[-(3.74 \times 10^6/T)]}{(1 - e^{-3390/T})} \right\}^{1/3}$	$\left\{ \begin{array}{c} \text{or} \\ \text{or} \end{array} \right\}$		$T = 3000-4500 \text{ K}$	

Table 24-1. (Cont'd.)

No.	Reaction	a	b	c	Notes	Sources
XXXIV. Collisional Vibrational-State Quenching (Cont'd.):						
4.	$N_2(v=1) + N_2 \rightarrow N_2(v=0) + N_2$	$\left\{ 1.3 \times 10^{-11} T \exp[-(1.06 \times 10^7/T)] \right\}^{1/3}$			$T = 300-5000 \text{ K.}$	Chp. 20 (Table 20-2)
XXXV. Collisional Vibrational Energy Exchange:						
1.	$O_2(v=1) + H_2O \rightarrow O_2(v=0) + H_2O(010)$	$(1.7) \times 10^{-11} \pm 1$	(-0.5)	0	Endothermic by 39 cm^{-1} ($\sim 0.005 \text{ eV}$)	Chp. 20 (Table 20-5)
2.	$N_2(v=1) + O_2(v=0) \rightarrow N_2(v=0) + O_2(v=1)$	$\left\{ \frac{2.5 \times 10^{-7} \exp[-(1.82 \times 10^7/T)]}{(1 - e^{-3390/T})} \right\}^{1/3}$			$T = 1000-10,000 \text{ K}$	Chp. 20 (Table 20-2)
3.	$N_2(v=1) + N_2(v=0) \rightarrow N_2(v=0) + N_2(v=1)$	$(3) \times 10^{-13} \left[\begin{smallmatrix} +1.5 \\ -0.3 \end{smallmatrix} \right]$	0	0	Case of resonant VV at $T = 300 \text{ K.}$	
4.	$N_2(v=1) + CO_2(000) \rightarrow N_2(v=0) + CO_2(001)$	$(6 \pm 2) \times 10^{-13}$	(-0.5)	0	$T = 300-1200 \text{ K}$	

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